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RESEARCH MEMORANDUM

PRESSURE DRAG OF AXISYMMETRIC COWLS HAVING LARGE INITIAL LIP ANGLES AT MACH NUMBERS FROM 1.90 TO 3.88

By Nick E. Samanich

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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4597

SUMMARY

The results of experimental and theoretical data on nine cowls are presented to determine the effect of initial lip angle and projected frontal area on the cowl pressure drag coefficient at Mach numbers from 1.90 to 3.88. The trends in cowl pressure drag coefficient were approximated well with two-dimensional shock-expansion theory at the lower cowl projected areas, but the digression from the data became increasingly greater as the cowl area ratio was increased and shock detachment at the cowl lips was approached. An empirical chart is presented which can be used to estimate the cowl pressure drag coefficient of cowls approaching an elliptic contour.

CB-1

INTRODUCTION

Evaluation of cowl designs for high-speed flight is a necessary part of a preliminary performance analysis. Several theoretical approaches are available which give satisfactory agreement with experimental pressure drag data on unity-mass-flow engine cowls in certain isolated regions. The linearized source distribution method gives satisfactory results except for cases where the Mach number or the body slopes are large (refs. 1 and 2). Van Dyke's second-order supersonic flow calculations are limited to maximum slopes corresponding to angles of approximately 28°, 18°, and 13° at Mach numbers of 2, 3, and 4, respectively (ref. 3). The shock-expansion method (refs. 4, 5, and 6) neglects reflection of disturbances originating at the surface as well as the three-dimensional effect. The degree to which the local disturbances are reflected is small except at large lip angles (near shock detachment values). It is in this area, lip angles near shock detachment values in the range from Mach 2.0 to 4.0, that experimental data are needed, because most of the approximate methods of estimating pressures deviate appreciably from the exact values.

Some recent empirical drag measurements have been reported in reference 7 on a family of ducted biconic bodies at Mach numbers of 2.00, 2.50, and 2.77, but no attempt was made to compare the results with theory. The only satisfactory method of predicting cowl drags theoretically in this area appears to be with the use of rotational characteristics. This method of solution is quite tedious and time-consuming even when computed with automatic computing equipment. In view of the items discussed and the lack of sufficient systematic experimental testing in this area, the program reported herein was initiated at the NACA Lewis laboratory. 4597

MODELS AND APPARATUS

An investigation of existing cowl designs indicated that an elliptic contour closely approximated the majority of shapes examined. A family of nine elliptically contoured cowls was designed which incorporated large initial lip angles near the detachment value at Mach numbers from 2.0 to 4.0. The contour from the lip to the constant-6-inch-diameter section (see fig. 1 and table I) on the steel models was defined by the elliptic equation $Y_0 = 0.441\sqrt{a^2 - X_0^2}$ where X_0 and Y_0 are the rectangular coordinates and the constant a was varied to give initial nominal lip angles of 20°, 28°, and 34° and projected cowl areas of 20, 35, and 50 percent of the maximum frontal area. Static-pressure orifices were located externally on the cowls at axial distances from 0.060 inch aft of the lip to the constant-diameter section. The internal contour of the cowls was a straight diverging taper from the cowl lip to the cowl exit. All the cowls had sharp lips with a maximum radius of 0.0025 inch. Scaled drawings of the external contours are shown in figure 1, and photographs of three typical models are presented in figure 2. The models were strut-supported and tested in several of the Lewis small supersonic wind tunnels at zero angle of attack. The Reynolds number was held relatively constant during the fixed Mach number runs and had values of 5.2×10^6, 6.1×10^6, 4.9×10^6, and 1.1×10^6 per foot at the respective test free-stream Mach numbers of 1.98, 2.47, 2.94, and 3.88.

RESULTS AND DISCUSSION

The experimental surface pressure coefficients are listed as a function of axial distance from the lip in table II. Figure 3 is a representative plot showing the longitudinal pressure distribution for both the experimental and theoretical results of the 34° initial lip angle cowls at a Mach number of 3.88. The trends are closely approximated with theory at the smaller projected areas but deviate progressively as the projected cowl areas are increased.

The experimental pressures were integrated over the cowl surfaces and the resultant drag coefficients, based on a maximum cross-sectional area of 0.787 square foot, were compared with values calculated using two-dimensional shock-expansion theory in all cases where attached shock waves existed. No attempt was made to calculate theoretical drag coefficients when detached waves existed at the cowl lips, but estimates can be made with the aid of reference 8.

Figure 4 shows the effect of lip angle, projected cowl area, and Mach number on the cowl pressure drag coefficients. The theoretical results are shown only for attached shock conditions at the lip. While the trends are approximated rather well with shock-expansion theory at the lower projected cowl areas, the deviation between theory and experiment becomes increasingly greater as the area ratio is increased. This deviation with increasing area ratio can be attributed to the greater variation in radius (a larger three-dimensional effect). In most cases, the theoretical results indicated a rather sharp rise in drag as the shock detachment value was approached at the lip. The experimental data, in general, revealed no abrupt changes when theoretical shock detachment had been attained at the lip. In the schlieren photographs in figure 5, shock detachment at the lip was not apparent until Mach numbers substantially lower than theoretically predicted had been reached. This was probably due to the fact that the initial lip angle was not maintained for any appreciable axial distance.

Although no data are presented, several of the cowls were run at two Reynolds numbers at Mach 2.94. A small effect was noted which resulted in drag coefficients 3 to 5 percent higher for the cowls tested at a Reynolds number of 2.5×10^6 as compared with those tested at 4.9×10^6 per foot.

The experimental data are combined in figure 6 as an empirical chart for use in estimating the cowl pressure drag coefficient for cowls approximating or having an elliptic external contour. The constant-area ratio lines were located arbitrarily in a manner such that the experimental data for given initial lip angles resulted in definite trends. The symbols in figure 6 are the actual experimental data obtained. As an example of the use of the chart, the cowl pressure drag coefficient at Mach 3 of an elliptically contoured cowl, having a cowl projected area 25 percent of the total frontal area and an initial lip angle of 30°, would be found by following the arrows as shown in figure 6, resulting in an approximate drag coefficient of 0.10.

CONCLUDING REMARKS

The results revealed that the trends in cowl pressure drag coefficient could be approximated rather well with two-dimensional shock-expansion theory at the lower projected cowl areas, but the deviation between theory and experiment becomes increasingly greater as the projected cowl area ratio is increased and shock detachment at the cowl lips is approached. An empirical chart was developed from the experimental data enabling the estimation of cowl pressure drags for cowls having or approximating elliptic external contours. 4597

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 25, 1957

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2. Jack, John R.: Theoretical Wave Drags and Pressure Distributions for Axially Symmetric Open-Nose Bodies. NACA TN 2115, 1950.

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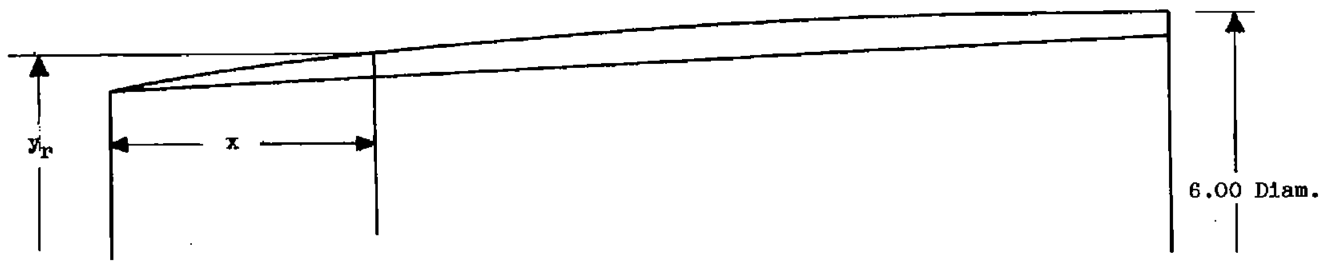
TABLE I. - COWL COORDINATES

[All dimensions in inches.]



Cowl 1		Cowl 2		Cowl 3		Cowl 4		Cowl 5		Cowl 6		Cowl 7		Cowl 8		Cowl 9	
x	y_r	x	y_r	x	y_r	x	y_r	x	y_r	x	y_r	x	y_r	x	y_r	x	y_r
0	2.685	0	2.420	0	2.124	0	2.685	0	2.420	0	2.124	0	2.685	0	2.420	0	2.124
.10	2.712	.10	2.447	.10	2.151	.10	2.732	.10	2.467	.10	2.171	.10	2.750	.10	2.488	.10	2.192
.20	2.740	.20	2.473	.20	2.178	.20	2.775	.20	2.510	.20	2.217	.20	2.794	.20	2.542	.20	2.250
.40	2.782	.40	2.520	.40	2.230	.30	2.809	.30	2.553	.40	2.300	.30	2.833	.30	2.598	.40	2.359
.60	2.822	.60	2.570	.60	2.280	.40	2.843	.40	2.592	.60	2.380	.40	2.870	.40	2.648	.60	2.452
.80	2.859	.80	2.615	.80	2.330	.50	2.863	.60	2.665	.80	2.453	.60	2.924	.60	2.720	.80	2.534
1.00	2.891	1.00	2.653	1.00	2.377	.60	2.896	.80	2.735	1.00	2.518	.80	2.962	.80	2.792	1.00	2.806
1.20	2.917	1.20	2.700	1.20	2.430	.80	2.937	1.00	2.785	1.20	2.579	1.00	2.985	1.00	2.843	1.20	2.670
1.50	2.951	1.50	2.754	1.50	2.483	1.00	2.967	1.20	2.830	1.50	2.660	1.20	2.997	1.20	2.890	1.50	2.752
2.00	2.985	2.00	2.831	2.00	2.580	1.20	2.988	1.50	2.884	2.00	2.772	1.305	3.000	1.50	2.937	2.00	2.860
2.47	3.000	2.50	2.892	2.50	2.663	1.50	2.998	2.00	2.953	2.50	2.859			2.00	2.989	2.50	2.934
		3.00	2.940	3.00	2.738	1.57	3.000	2.50	2.991	3.00	2.923			2.40	3.000	3.00	2.980
		3.50	2.974	3.50	2.805			2.89	3.000	3.50	2.966					3.50	2.990
		4.00	2.995	4.00	2.857					4.00	2.989					3.63	3.000
		4.50	2.999	4.50	2.902					4.36	3.000						
		4.56	3.000	5.00	2.941												
				5.50	2.968												
				6.00	2.990												
				6.50	2.999												
				6.90	3.000												

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TABLE II. - EXPERIMENTAL PRESSURE DISTRIBUTIONS

Cowl 1

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -			
	1.98	2.47	2.94	3.88
0.07	0.510	0.400	0.345	0.312
.11	.468	.366	.315	.276
.16	.401	.320	.267	.242
.21	.368	.290	.232	.229
.28	.364	.285	.224	.196
.36	.315	.248	.208	.172
.44	.276	.223	.180	.162
.54	.258	.203	.157	.155
.64	.256	.208	.166	.140
.76	.224	.180	.153	.127
.90	.197	.162	.126	.114
1.05	.167	.134	.103	.103
1.20	.152	.127	.103	.088
1.36	.118	.097	.084	.071
1.55	.090	.071	.052	.060
1.90	.034	.030	.023	.032
2.40	-.006	-.003	.002	.006

Cowl 2

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -			
	1.98	2.47	2.94	3.88
0.07	0.506	0.413	0.350	0.323
.11	.456	.351	.292	.271
.16	.425	.337	.298	.249
.20	.421	.335	.291	.247
.30	.387	.318	.261	.229
.38	.370	.296	.257	.215
.48	.340	.287	.253	.200
.60	.337	.277	.231	.197
.74	.312	.250	.203	.181
.89	.280	.233	.195	.165
1.08	.257	.215	.188	.152
1.30	.233	.197	.165	.136
1.55	.187	.156	.125	.114
1.90	.145	.124	.101	.090
2.25	.104	.089	.082	.069
2.60	.087	.076	.070	.058
2.95	.071	.056	.050	.045
3.30	.037	.030	.028	.029
3.70	.008	.013	.008	.016
4.50	-.032	-.015	-.011	-.004

Cowl 3

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -			
	1.98	2.47	2.94	3.88
0.08	0.576	0.459	0.398	0.325
.12	.503	.380	.328	.289
.16	.468	.358	.309	.274
.22	.436	.337	.295	.251
.30	.435	.340	.309	.247
.40	.410	.326	.279	.238
.52	.381	.310	.267	.228
.66	.362	.283	.247	.208
.80	.342	.277	.241	.198
.98	.315	.251	.217	.185
1.18	.271	.221	.193	.164
1.40	.236	.189	.168	.139
1.65	.210	.173	.155	.126
1.90	.184	.157	.133	.113
2.20	.163	.140	.120	.100
2.50	.154	.131	.117	.093
2.75	.144	.126	.112	.088
3.25	.111	.097	.079	.072
3.75	.064	.056	.044	.047
4.25	.065	.042	.036	.037
4.75	.034	.036	.028	.027
5.25	.022	.018	.012	.021
6.00	-.014	-.013	-.010	.004
6.75	-.035	-.030	-.024	-.011

Cowl 4

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -			
	1.98	2.47	2.94	3.88
0.08	0.861	0.685	0.605	0.522
.11	.755	.610	.529	.446
.15	.675	.537	.459	.412
.21	.622	.503	.408	.381
.28	.594	.481	.427	.361
.35	.532	.449	.397	.328
.43	.471	.399	.338	.299
.53	.387	.324	.262	.247
.64	.320	.279	.244	.203
.76	.236	.195	.176	.154
.90	.191	.163	.133	.128
1.05	.135	.115	.090	.095
1.20	.082	.078	.063	.062
1.35	.013	.024	.023	.029
1.50	-.003	.006	.004	.019

Cowl 5

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -			
	1.98	2.47	2.94	3.88
0.08	0.914	0.756	0.693	0.563
.12	.810	.645	.621	.499
.16	.751	.595	.551	.462
.22	.723	.582	.508	.448
.28	.716	.592	.557	.440
.36	.675	.563	.534	.418
.44	.619	.529	.490	.405
.54	.568	.485	.443	.377
.64	.504	.437	.418	.333
.76	.414	.362	.349	.277
.90	.310	.273	.256	.224
1.04	.251	.220	.207	.183
1.20	.216	.201	.193	.152
1.36	.178	.160	.164	.129
1.54	.146	.135	.124	.107
1.90	.094	.090	.089	.076
2.35	.021	.034	.046	.037
2.80	-.034	-.014	-.001	.007

Cowl 6

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -			
	1.90	2.47	2.94	3.88
0.08	0.953	0.743	0.645	0.564
.12	.924	.711	.606	.538
.16	.845	.680	.584	.508
.22	.773	.642	.554	.492
.30	.732	.629	.559	.475
.38	.661	.588	.515	.453
.50	.585	.530	.461	.407
.74	.464	.436	.391	.336
.90	.394	.382	.325	.293
1.08	.336	.331	.284	.255
1.30	.288	.290	.257	.227
1.55	.238	.246	.221	.194
1.90	.172	.189	.160	.151
2.25	.102	.138	.118	.111
2.60	.064	.103	.089	.087
2.95	.031	.068	.058	.065
3.30	-.012	.037	.036	.041
3.70	-.053	.008	.009	.025
4.30	-.078	-.014	-.011	.006

Cowl 7

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -			
	1.98	2.47	2.94	3.88
0.08	1.116	1.009	0.909	0.773
.12	.968	.877	.783	.649
.16	.875	.782	.685	.582
.22	.713	.633	.539	.499
.28	.596	.535	.480	.400
.36	.486	.438	.390	.334
.44	.424	.384	.325	.288
.54	.343	.299	.249	.241
.64	.278	.251	.224	.187
.76	.194	.172	.160	.143
.88	.128	.125	.101	.107
1.00	.080	.081	.067	.073
1.12	.035	.043	.036	.056
1.26	.011	.027	.028	.035
1.40	-.009	.008	.014	.026

Cowl 8

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -			
	1.98	2.47	2.94	3.88
0.08	1.230	1.103	0.995	0.832
.12	1.126	1.011	.922	.771
.16	1.013	.897	.804	.711
.22	.902	.802	.698	.640
.28	.823	.738	.690	.576
.36	.737	.659	.613	.511
.44	.620	.564	.509	.446
.54	.534	.478	.422	.390
.64	.482	.440	.411	.339
.76	.410	.367	.343	.285
.90	.324	.297	.263	.236
1.08	.254	.233	.203	.192
1.24	.203	.196	.181	.148
1.42	.145	.142	.138	.114
1.62	.090	.092	.083	.084
1.92	.038	.050	.050	.055
2.42	-.031	-.007	.009	.010

Cowl 9

Axial distance aft of lip, x, in.	Surface pressure coefficient at Mach numbers of -			
	1.90	2.47	2.94	3.88
0.08	1.226	1.074	0.939	0.799
.11	1.116	.973	.871	.733
.16	1.051	.897	.789	.691
.22	.973	.846	.734	.668
.30	.903	.836	.748	.639
.38	.819	.783	.712	.606
.48	.723	.707	.635	.553
.60	.652	.567	.498	.467
.74	.485	.497	.460	.397
.90	.400	.425	.391	.334
1.08	.327	.349	.309	.282
1.30	.252	.279	.241	.231
1.55	.202	.238	.213	.186
1.90	.128	.168	.154	.135
2.25	.050	.095	.067	.092
2.60	-.001	.094	.052	.063
2.95	-.039	.024	.031	.033
3.25	-.057	-.003	-.001	.017
3.60	-.081	-.016	-.006	.012

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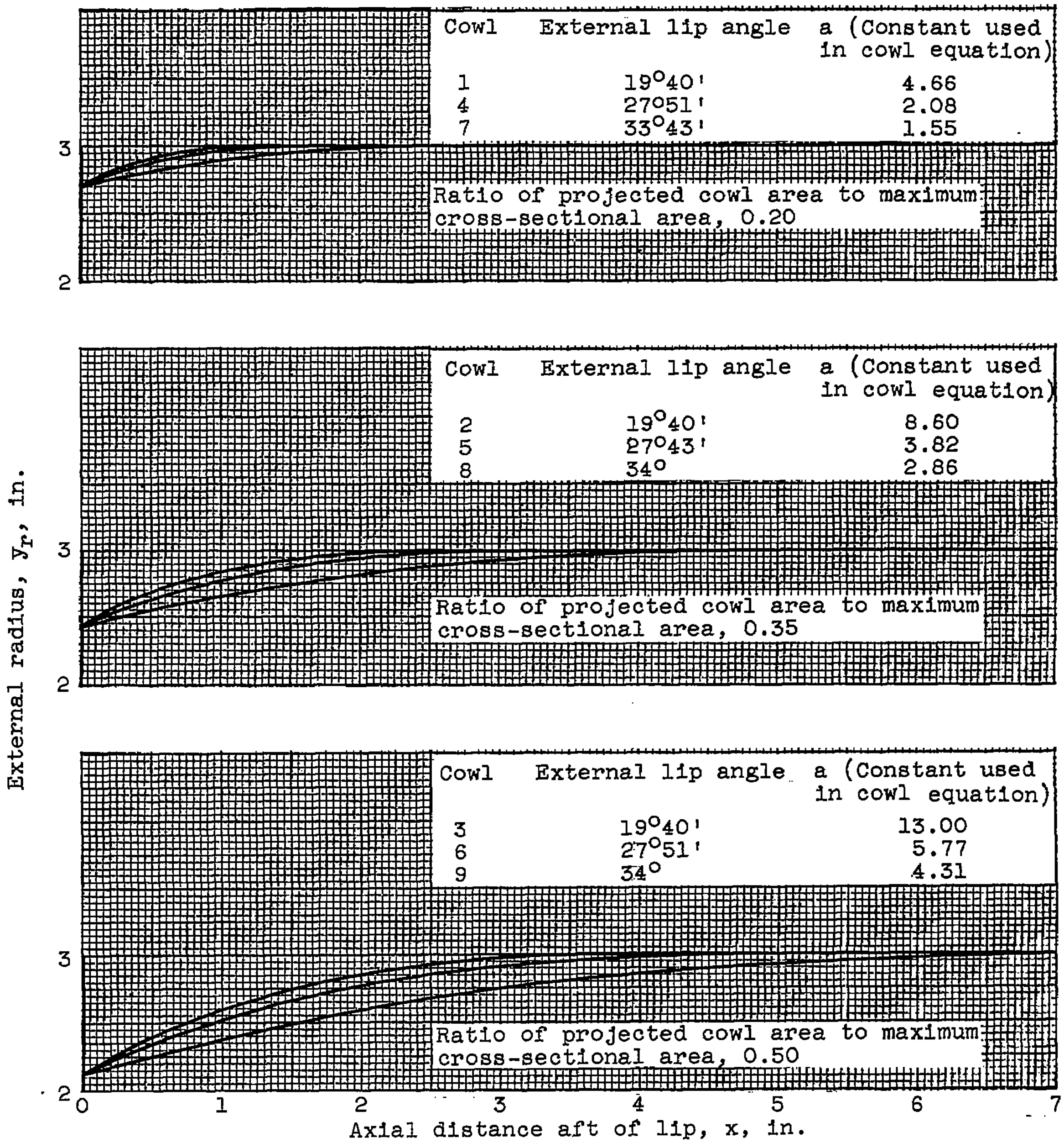

Figure 1. - Scale drawings of cowls defined by the cowl equation $Y_0 = 0.441\sqrt{a^2 - X_0^2}$.

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(a) Cowl 7.

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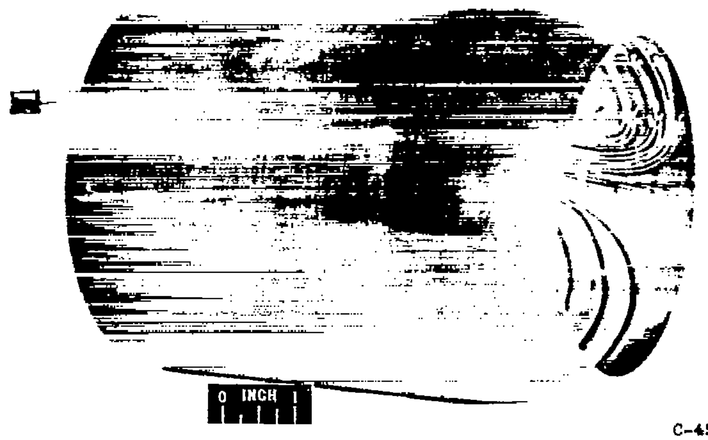
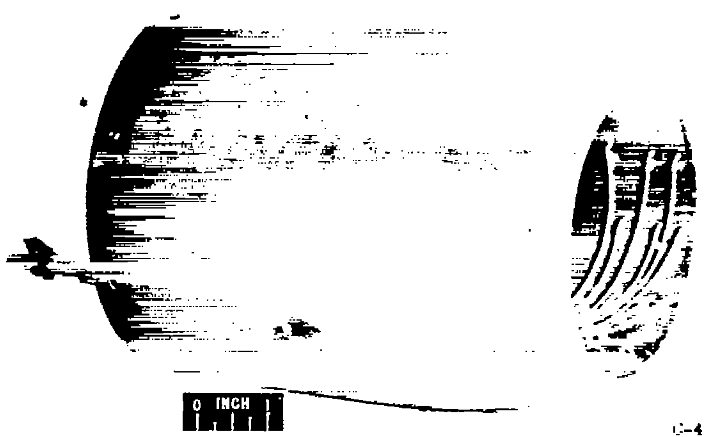


C-45073

(b) Cowl 8.



C-45074

(c) Cowl 9.

Figure 2. - Cowls 7, 8, and 9.

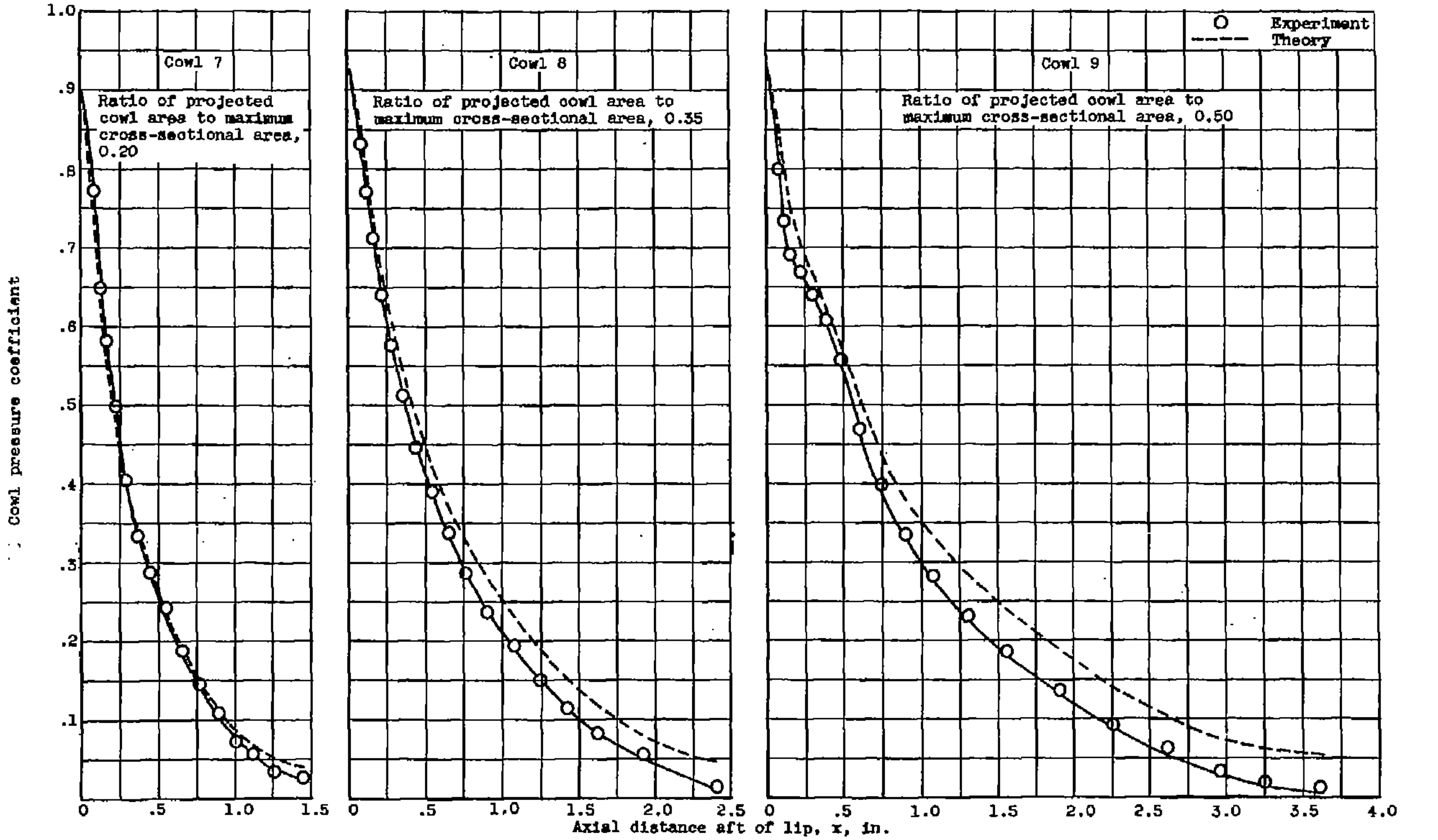
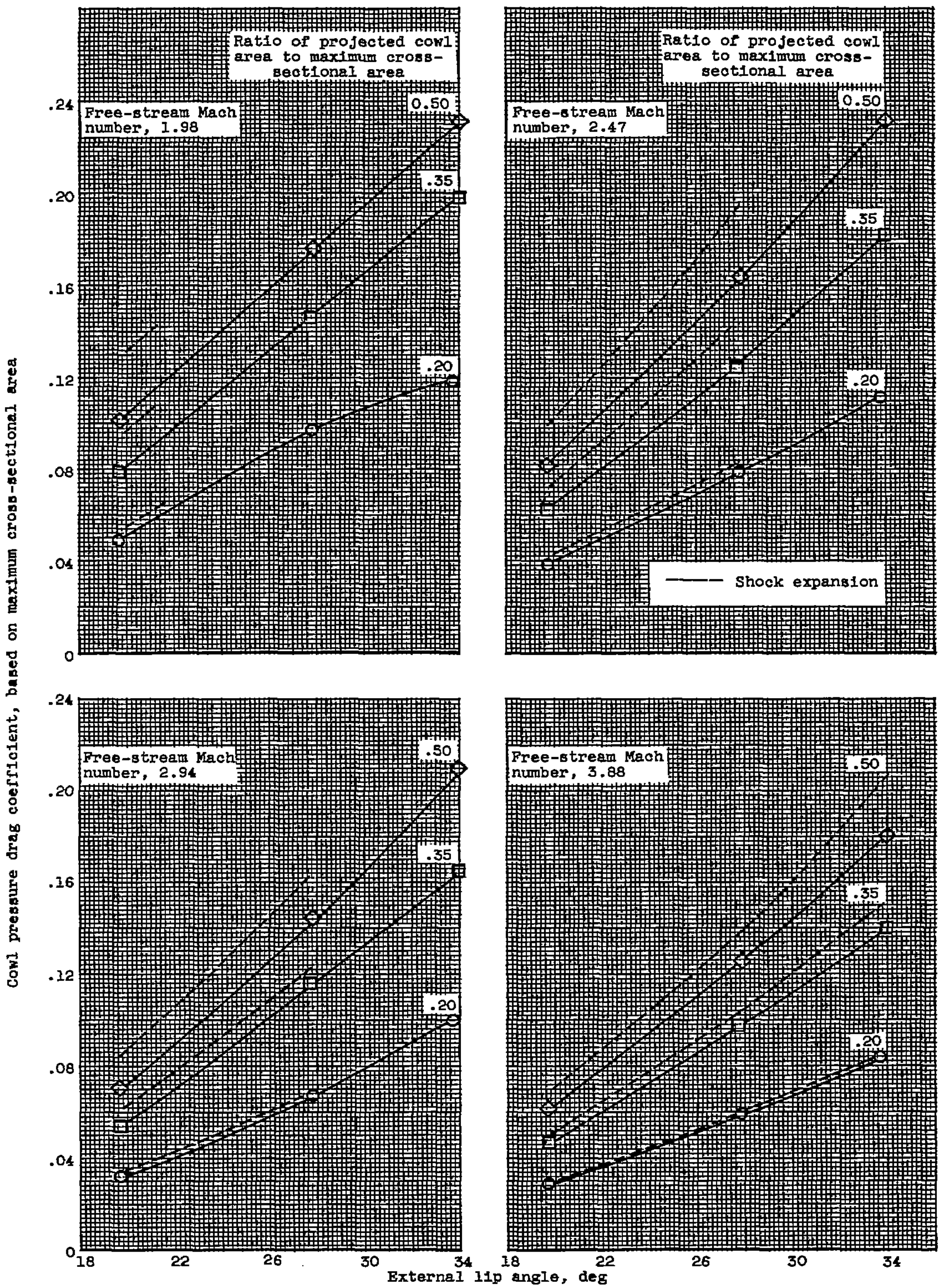


Figure 3. - Comparison of experimental and theoretical cowl pressure distributions. External lip angle, 34°; free-stream Mach number, 3.88.



(a) External lip angle.

Figure 4. - Effects of lip angle, projected cowl area, and Mach number on cowl pressure drag coefficients.

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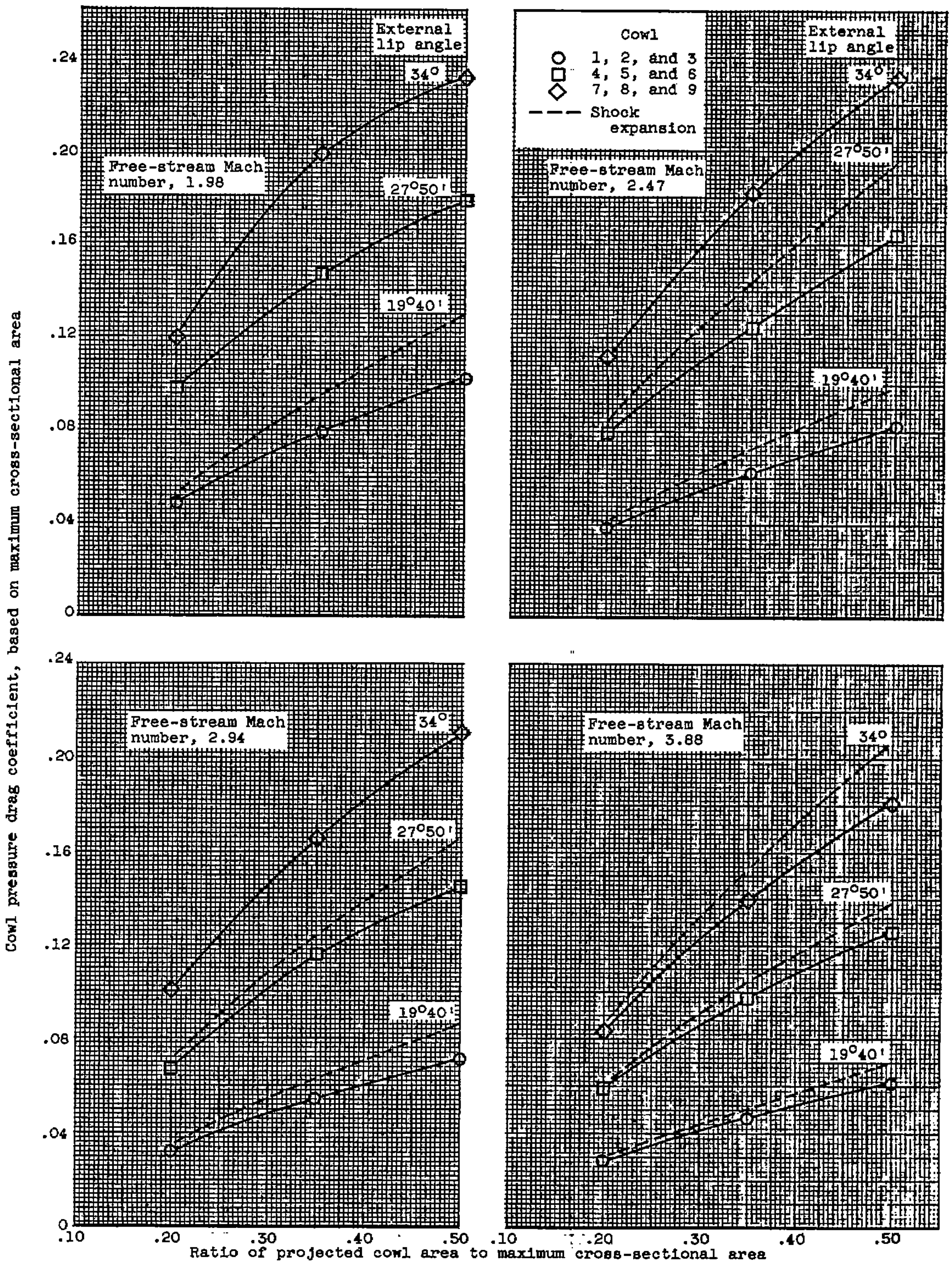
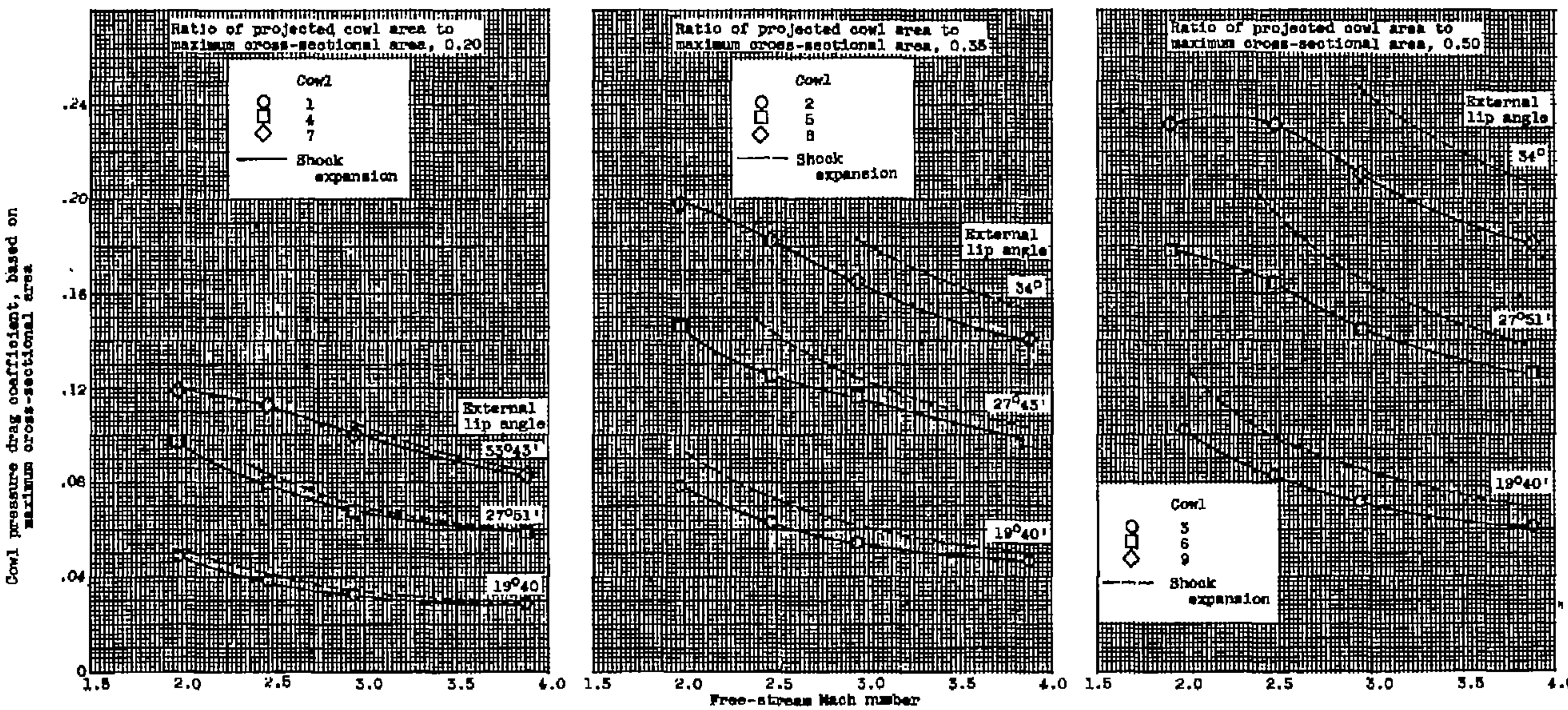


(b) Projected cowl area.

Figure 4. - Continued. Effects of lip angle, projected cowl area, and Mach number on cowl pressure drag coefficients.



(c) Mach number.

Figure 4. - Concluded. Effects of lip angle, projected cowl area, and Mach number on cowl pressure drag coefficients.

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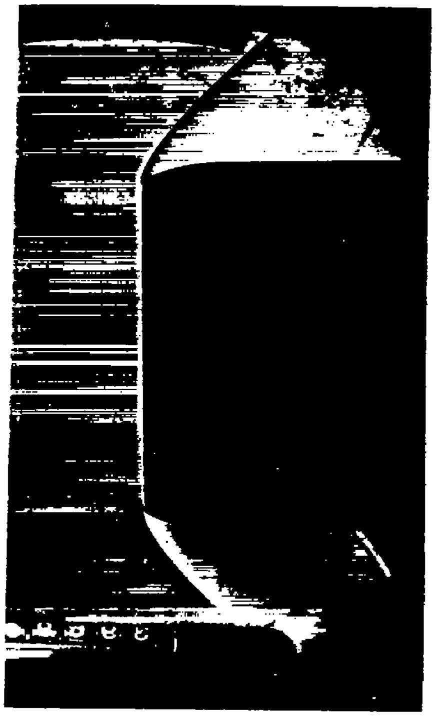
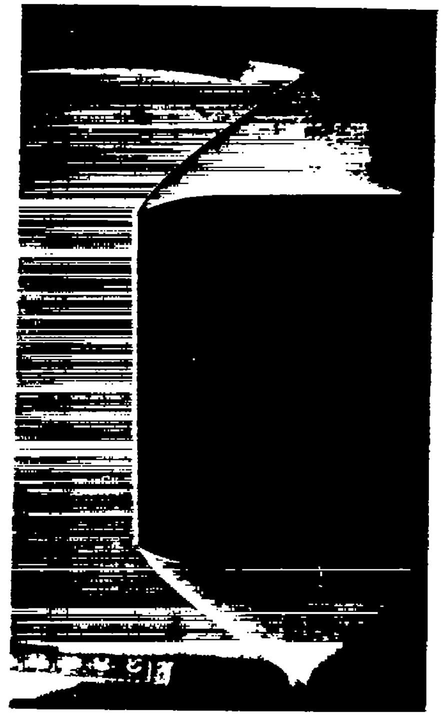
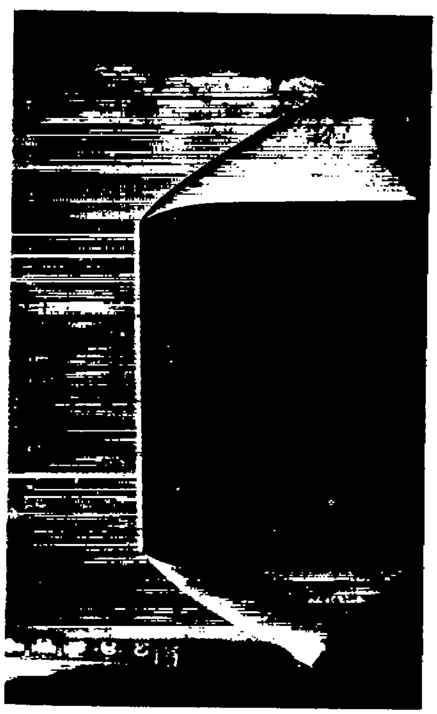


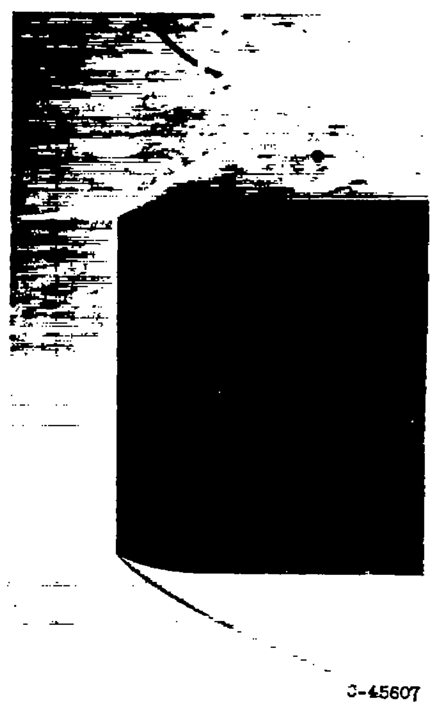
Free-stream Mach number, 1.98



Free-stream Mach number, 2.47



Free-stream Mach number, 2.94



Free-stream Mach number, 3.88

Figure 5. - Schlieren photographs of cowl 7.

NACA - Langley Field, Va.

[redacted]

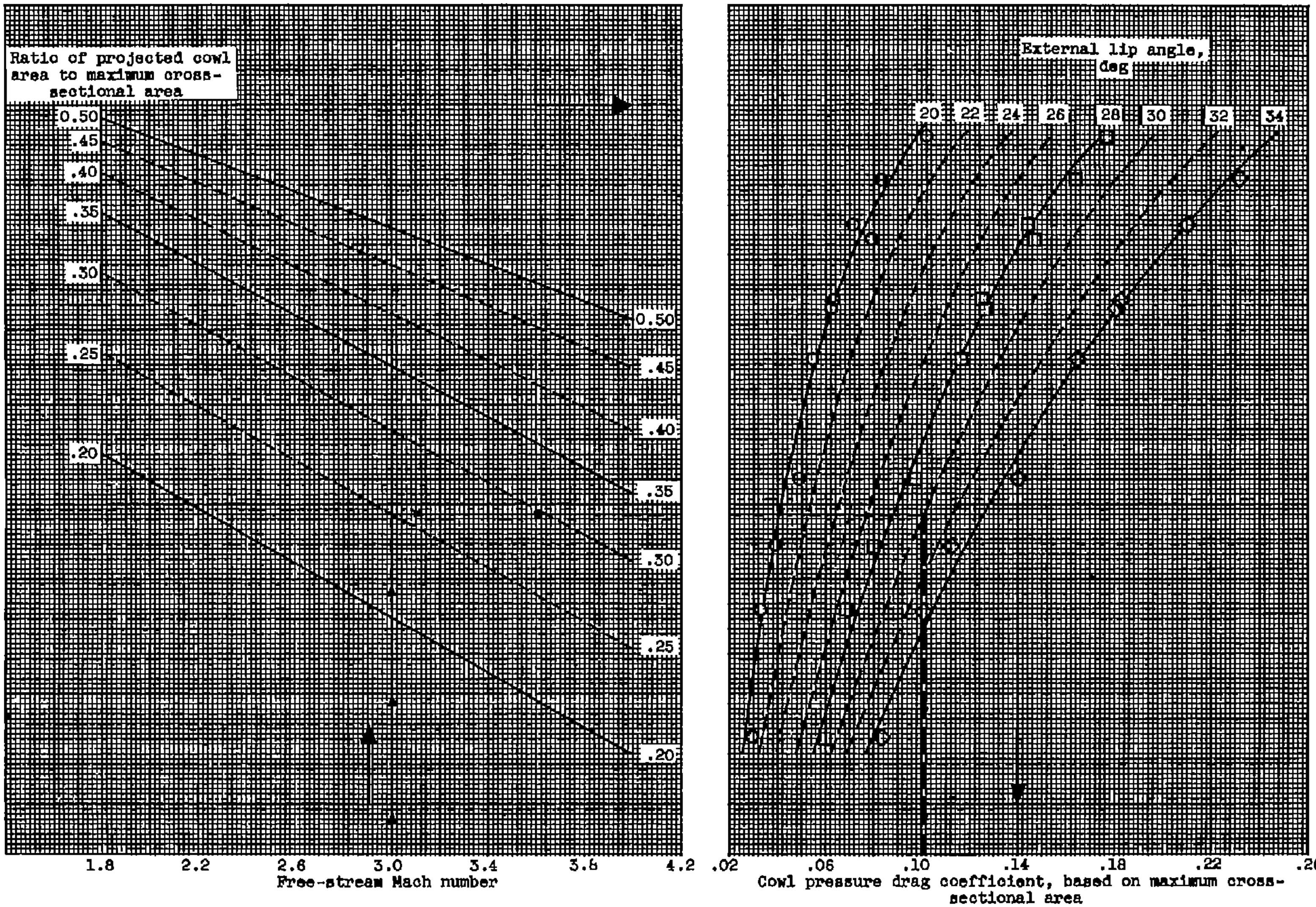
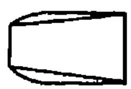
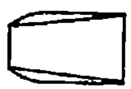
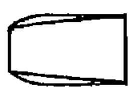
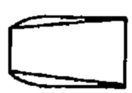


Figure 6. - Empirical chart for estimating elliptical cowl pressure drag coefficients.

NOTES: (1) Reynolds number is based on the diameter of a circle with the same area as that of the capture area of the inlet.

(2) The symbol * denotes the occurrence of buzz.

Report and facility	Description			Test parameters				Test data				Performance		Remarks
	Configuration	Number of oblique shocks	Type of boundary-layer control	Free-stream Mach number	Reynolds number $\times 10^{-6}$	Angle of attack, deg	Angle of yaw, deg	Drag	Inlet-flow profile	Discharge-flow profile	Flow picture	Maximum total-pressure recovery	Mass-flow ratio	
CONFID. RM E57G24 1- by 1-foot variable Reynolds number jet and 2- by 2-foot supersonic wind tunnel		Normal	None	1.98 to 3.88	0.39 to 2.72	Zero	Zero	√				Not measured	1.0	Cowl pressure drag measurements are made on nine elliptically contoured cowls with large initial lip angles and various projected cowl areas.
CONFID. RM E57G24 1- by 1-foot variable Reynolds number jet and 2- by 2-foot supersonic wind tunnel		Normal	None	1.98 to 3.88	0.39 to 2.72	Zero	Zero	√				Not measured	1.0	Cowl pressure drag measurements are made on nine elliptically contoured cowls with large initial lip angles and various projected cowl areas.
CONFID. RM E57G24 1- by 1-foot variable Reynolds number jet and 2- by 2-foot supersonic wind tunnel		Normal	None	1.98 to 3.88	0.39 to 2.72	Zero	Zero	√				Not measured	1.0	Cowl pressure drag measurements are made on nine elliptically contoured cowls with large initial lip angles and various projected cowl areas.
CONFID. RM E57G24 1- by 1-foot variable Reynolds number jet and 2- by 2-foot supersonic wind tunnel		Normal	None	1.98 to 3.88	0.39 to 2.72	Zero	Zero	√				Not measured	1.0	Cowl pressure drag measurements are made on nine elliptically contoured cowls with large initial lip angles and various projected cowl areas.

Bibliography

These strips are provided for the convenience of the reader and can be removed from this report to compile a bibliography of NACA inlet reports. This page is being added only to inlet reports and is on a trial basis.